PROBLEM DELINEATION: AUTOMOBILE RESTRAINT SYSTEMS*

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THREE principles essential to protect motor vehicle occupants are an intact occupant compartment, energy absorption external to the occupant compartment, and occupant restraint within the compartment. Recognition of these principles and their application to transportation vehicles, particularly to automobiles, has required most of this century.

Historically, three scientists are giants in the field of occupant protection. The first is Hugh DeHaven, an engineer and World War I fighter pilot. World War I fighter planes were equipped with safety belts to hold the pilots in the plane during acrobatics.[1] DeHaven crashed while wearing such a safety belt and lacerated his liver, pancreas, and gall bladder. His upper abdomen was bluntly impacted by an 6-inch wide buckle on the lap belt. Fortunately, he survived this nearly fatal injury. Following his convalescence he initiated an accident investigation study of military plane crashes. He discovered that injuries caused by the wide lap belt buckle and by other parts of the cockpit were common. He recommended design changes to eliminate or to reduce injury risks. His recommendations were not viewed with favor by his superiors, who believed that the only function of a lap belt was to hold pilots in place while the plane was upside down. The accident injury control potential of lap belts was not recognized except by DeHaven.

After World War I DeHaven was discharged, and for 15 years he put aside his restraint system and accident research. In 1935 he witnessed, as a passenger, a minor motor vehicle accident. The driver struck his head on the metal windshield wiper control knob and sustained a penetrating injury of his right frontal sinus and a laceration across his nose and left eye. A rubber wiper control would have prevented the injuries. He recognized that engi-

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neers did not know and that nobody knew how many motorists were unnecessarily killed or injured by objects inside motor vehicles which could be modified or eliminated to prevent injury.

Because of this incident, he again became interested and collected records of apparently miraculous survivals from falls from 50 to 150 feet.[2] Mathematical analysis of each of these cases established that human survival was possible despite high speed. DeHaven resumed his accident research by establishing the crash injury research program at Cornell University Medical College. The program shifted to the newly established Cornell Aeronautical Laboratory after World War II and continues now as Calspan Field Services, Inc.

Shortly after World War II, a U.S. Army Air Force physician, John P. Stapp, saw the potential safety benefits of lap belt and shoulder harness restraint systems introduced on World War II aircraft by DeHaven. He also recognized the almost total lack of knowledge of human tolerances for injury. Jet engines and ejection seats were being introduced in military aircraft.[3,4] Improved restraint systems and other occupant protection devices for military pilots were urgently needed. A program of laboratory research utilizing acceleration sleds was initiated. Human volunteers, animals, cadavers, and anthropomorphic dummies were used to determine the human body's tolerance for deceleration and to improve restraint system design. Stapp volunteered himself as a subject for what historically proved to be the ultimate human tolerance test. He survived deceleration of 49 g although he sustained multiple soft tissue and skeletal injuries. Stapp's research became the basis for the occupant protection system used in America's man in space program.

Stapp recognized that the technology developed from his research could be applied to automobiles to reduce the risk of injury and death from motor vehicle accidents. In 1956 the first Stapp Car Crash Conference was held in Alamogordo, N.M., at Holloman Air Force Base, where Stapp was conducting his acceleration sled tests. Invited representatives came from the automobile manufacturing industry and researchers in medicine and engineering concerned with automobile safety and injury control. The Stapp conference has become a prestigious forum for research in vehicle design, human injury tolerance, and injury control.

The third giant is Dr. William Haddon, Jr. Dr. Haddon was a graduate of the Massachusetts Institute of Technology and Harvard Medical School. His engineering training gave him a clear understanding of the potential effectiveness of motor vehicle occupant protection systems and particularly of restraint systems. During his early career as a member of the New York State Department of Health, he clearly established a relationship between drinking and pedestrian-motor vehicle accident fatalities.[5] The first administrator of the National Highway Safety Bureau, now the National Highway Traffic and Safety Administration, he was appointed by President Lyndon Johnson when the bureau was established in 1966. Dr. Haddon wrote the first Federal Motor Vehicle Safety Standards. These are the standards that have made available to the motoring public in the United States the many occupant protection and design features currently available to us. All cars sold in the United States have to meet them.

In 1972 the administration of the U.S. government changed, and Dr. Haddon left his government position to establish the Insurance Institute for Highway Safety. He remained president of this until his untimely death in 1987. During those years he built the Insurance Institute for Highway Safety into a highly efficient and widely respected research organization. Dr. Haddon's successor and the current president of the Insurance Institute for Highway Safety is Dr. Brian O'Neil. The Institute has supported studies through intramural and extramural research funding that have become milestones in injury control research.

Another contribution of Dr. Haddon's was a book, *Accident Research, Methods and Approaches*.[6] Although the book is out of print, it is available in most medical and engineering libraries, and is an encyclopedia of injury control research. Dr. Haddon reprinted and carefully analyzed key publications in injury control research.

Two other scientists are major contributors to the development of occupant protection systems. Dr. Bertil Aldman, a Swedish anesthesiologist, and Nils Bohlin, a safety engineer for Volvo Automobile Company, developed the 3-point safety belt system now used worldwide in mass produced automobiles. Dr. Aldman's Ph.D. thesis is an account of the research that revealed the necessary injury tolerance and anthropometric knowledge essential for design of the restraint system.[7] Bohlin provided the engineering capability for its introduction in Volvo automobiles in 1959. An insurance report study of all Volvo accidents in Sweden clearly established the system's enormous injury control capabilities in 1967.[8] In this study there were no fatalities among restrained occupants in crash speeds below 60 mph. For unrestrained occupants fatalities occurred with crash speeds as low as 12 MPH. This landmark study provided the principal research basis to extend the Federal Motor Vehicle Safety Standards in 1968 to require shoulder harnesses. Prior to this change only lap belts were required.

Principles of Occupant Protection

The first principle of occupant protection is an intact occupant compartment. Significant changes in vehicle design and construction occurred in the early 1930s when all steel automobile bodies were introduced. Prior to this time, wood was used in structural elements of the body and leather or synthetic fabrics were used for the top. In 1935 General Motors introduced the "turret top," a single piece of stamped steel covering the entire roof of the vehicle. Use of steel throughout the body very significantly improved the crashworthiness of automobiles.

Immediately after World War II, Daimler-Benz recognized the importance of the intact occupant compartment in a crash and the necessity of providing energy absorption external to the occupant compartment. Bela Barenyi of Daimler-Benz was granted a patent in 1951 based on these concepts. The crushable front end was first introduced on the Mercedes 180 in 1953. Swedish manufacturers quickly adopted the concepts to their own designs during the late 1950s and early 1960s.

The second principle of occupant protection is energy absorption. Crushable vehicle structure must be available to absorb crash energy. The front end most commonly performs this task. Head-on collisions are the most common collisions resulting in serious injury. The engine compartment, hood, front fenders, and frame stubs are all made of sheet metal in unit body cars, and are now designed to crush progressively. Only a very few remaining models utilize a separate body frame structure in which much heavier steel is used in the frame. Energy absorbing designs are now routinely incorporated in body structure. Transverse placement of the engine, a design utilized in most front drive cars, provides addtional crush distance, enhancing the energy absorbing capabilities of the front end (Figure 1).

The third principle of occupant protection is prevention of the second impact, a concept first described by Hugh DeHaven.[1] The first impact is that of the car with whatever it strikes—another vehicle, tree, or some fixed object. The second impact is that of the occupant with the inside of the car. In a typical head-on collision into a tree at 35 MPH, the car crushes and stops in a distance of 20-30 inches during a period of approximately a 10th of a second, 100 milliseconds. During that time the occupant moves forward from his seated position into the forward structures of the car—the windshield, the dashboard, or the steering wheel (Figure 2).

Fig. 1. Sheet metal, particularly sheet steel, is a very efficient energy absorption mechanism. Automobile front end crush sustained in the typical highway accident provides occupant compartment decelerations which are survivable with injuries of AIS-2 or less.

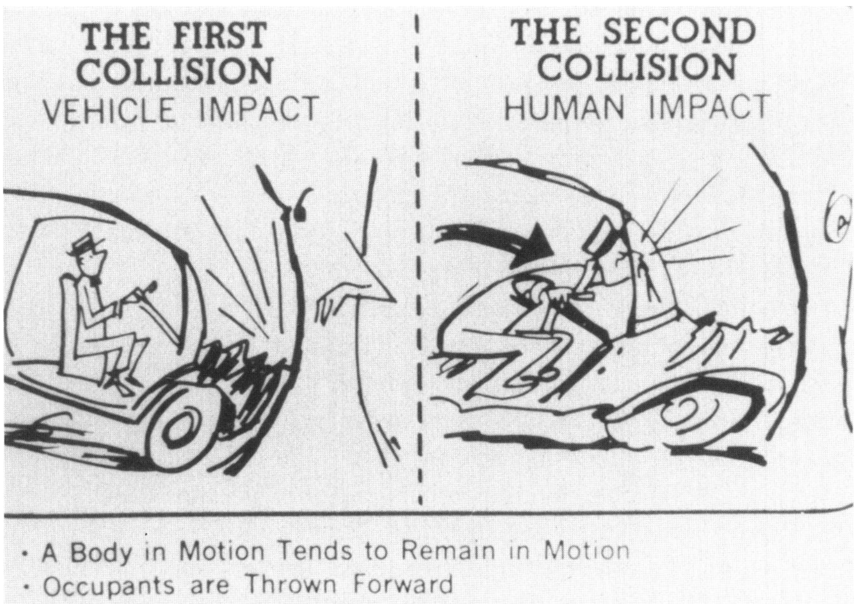


Fig. 2. The first collision is that of the vehicle with an external object. The second collision is that of the occupant with the interior of the vehicle and is the collision causing injury. Reprinted with permission from Physicians for Automobile Safety, Inc.

About the time the occupant reaches these structures, the car has stopped and the occupant is still moving at the original rate of speed of the vehicle. The distance in which the occupant is stopped is typically only a few inches. This distance represents the cracking of the windshield, the crush of the dashboard, and/or the collapse of the steering column and the crush of the occupant's own body structures; his face, head, chest, abdomen, or upper extremities. The time used to stop the occupant is far less than the time used to stop the vehicle, approximately 10 milliseconds. This shortened time and distance produces very high accelerations which produce the forces that cause serious injuries.

The key to protecting the occupant is to tie the occupant to the inside of the vehicle. Why are restraint systems so effective in preventing injury? Why does riding down with the vehicle avoid the serious injuries which so frequently occur in motor vehicle collisions?

The lap belt restrains most of the human body. The lap belt anchors the body of the occupant at about its center of gravity, which is located in a horizontal plane of a standing human being at the level of the anterior superior iliac spines.[9] This is below the waistline and below the brim of the pelvis, the illiac crests. Lap safety belts must positioned below this to insure bowstringing of the lap belt across the front of the bony pelvis. In this position, the lap belt will not injure the organs of the abdomen—the intestines, bladder, liver, spleen, and kidneys (Figure 3).

The second part of the occupant restraint system is the shoulder belt, designed to keep the head and upper torso from impacting the windshield and steering wheel. The belt goes over the clavicle and upper chest and crosses the abdomen. Occasionally fractures of the clavicle and ribs occur because of a shoulder belt, but this is an acceptable trade-off. Injuries to the head and chest sustained with only lap belt restraint are far more serious. Clavicle and rib fractures usually heal with minimal treatment and seldom cause significant complications (Figure 4).

Figure 5 is a series of photographs of a volunteer in a 17 MPH impact test. The subject was a young man in excellent physical condition who did his best to hold his arms at his side. In spite of his efforts, his arms, head, and neck were thrown straight forward despite his contracted musculature. This volunteer sled test illustrates the forces coming to bear on an occupant in a motor vehicle crash.

The unwritten goal of the Federal Motor Vehicle Safety Standards is to prevent serious injury, Abbreviated Injury Scale 3 or greater in a 30 MPH barrier impact equivalent crash.

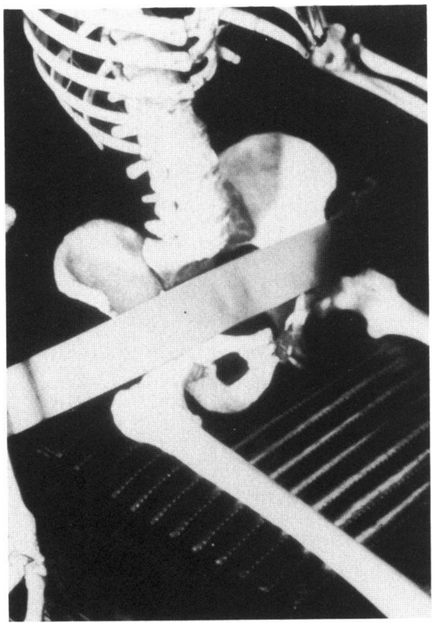


Fig. 3. The lap belt must be positioned below the anterior superior iliac spines (ASIS). The lap belt will bowstring across the bony pelvis and will not impinge on the soft part of the abdomen and the abdominal organs.

Fig. 4. The shoulder belt should be positioned over the clavicle and upper ribs. In this position it provides excellent restraint for the upper torso and head.

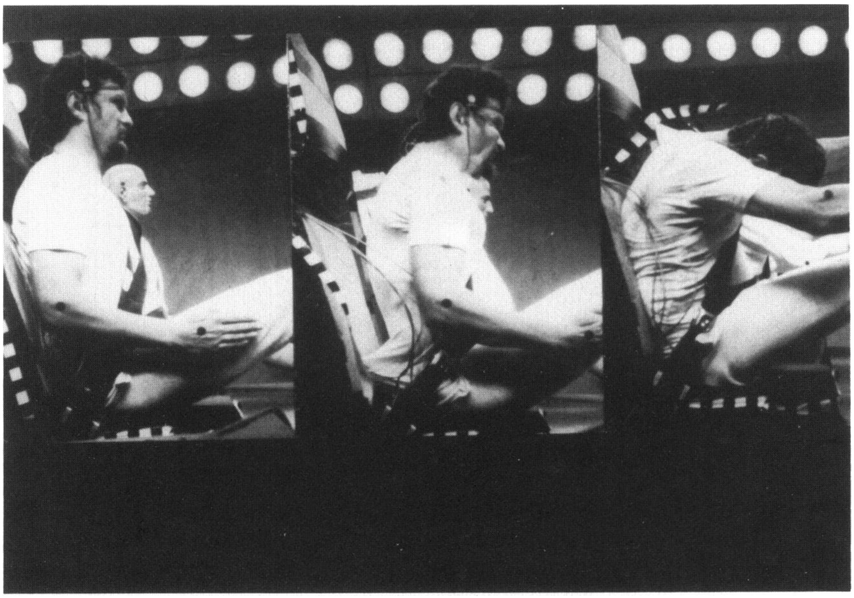


Fig. 5. The subject is a young man restrained with a three-point lap and shoulder belt system in a 17-mile-per-hour acceleration sled impact. Note that in spite of his tense musculature his head, upper torso, and upper extremities flailed forward. Reproduced courtesy of Calspan Coroporation.

History of Safety Belt Restraint Systems

The first documented use of a belt restraint system occurred in a 1908 World Race from New York to Paris when a lap belt was used to prevent a mechanic from falling out of a vehicle while asleep.[10] Combination lap and shoulder belt restraint systems were used in some World War I military airplanes. After World War I lap belts were occasionally used in racing.

Belt type restraint systems were widely used in World War II aircraft. These belt systems became available in the war surplus market after the war and were installed on some racing and road vehicles. The installations were haphazard because virtually no knowledge of human injury tolerances or biomechanics were available to guide installers during those years.

The first systematic research was begun, as earlier noted, at Cornell by Hugh DeHaven, assisted by Dr. Preston Wade, a trauma surgeon, and John Moore, an engineer. These studies were expanded nationwide, principally through state police agencies. Injury causation was carefully determined and the potential benefit of safety belt restraint systems projected. The studies provided research evidence that resulted in the first safety belts installed by vehicle manufacutrers. In 1956 Ford Motor Company offered an optional

Fig. 6. Ford Motor Co. introduced a Safety Package as optional equipment for the 1956 models. The package consisted of lap safety belts, a collapsible steering wheel, padded dashboard, and padded sunvisors.

safety package which included a lap-type safety belt (Figure 6).

Lap belts first appeared in 1949 in the Nash automobile manufactured by the American Motors Corporation. This belt was installed to support right front seat occupants in reclining seats. It was not intended as a safety belt but was the first commercially installed lap belt.

The 1956 Ford package included a dished-out collapsible steering wheel, a padded dashboard, padded sun visors, and lap belts. This was the industry's first effort to make safety belts widely available. Regrettably, Ford sold this package on only 3% of their 1956 model production. In 1955, when Ford and Chevrolet had introduced V8 engines, Ford outsold Chevrolet. In 1956 Chevrolet outsold Ford with promotions based on speed and performance and not safety. Following this experience, the entire industry concluded that safety could not be sold and may actually deter a purchaser by reminding him that an accident might occur.[11]

Safety belts continued to be available as optional equipment but very few were sold. In 1961 New York State Senator Edward Speno recognized the need to mandate the installation of safety equipment in passenger cars, and he was responsible for a law enacted in New York State that required anchors for lap belts.[12] Prior to this law, safety belt anchor locations were haphazardly selected, sometimes in areas with insufficient strength to provide adequate anchorage. Occasionally gasoline lines and electrical wiring were damaged by these installations. Although the industry vigorously opposed the legislation, the bill passed, the first mandated automobile safety equipment opposed by the industry. In 1962 Wisconsin legislation required installation of the entire lap belt[13] and was followed by New York in 1964 and by several other states by 1966.

During the early 1960s Ralph Nader emerged on the scene. He attended meetings of the Stapp Car Crash Conference and the American Association for Automotive Medicine seeking technical knowledge concerning occupant protection in motor vehicle accidents. Subsequently he mobilized public opinion and assisted Congress in writing the National Traffic and Motor Vehicle Safety Act of 1966, which created the National Highway Safety Bureau, later to become the National Highway Traffic Safety Administration. This law provided the legal basis for the Federal Motor Vehicle Safety Standards, which now mandate the safety equipment available in passenger cars sold in the United States; FMVSS 208, 209, and 210 cover safety belt and other occupant restraint systems.

Air Bags

Historically, Ford Motor Company was the first to establish the capability of occupant restraint utilizing air bags.[14] In 1957 Ford built and tested a prototype system that proved that there was sufficient time to interpose an air bag between a motorist and the forward structures of the vehicle in a head-on collision.

Carl Clark, then working for Martin Marietta Aircraft Corporation, experimented with air bags as restraint systems for aircraft and space vehicles.[15] This culminated in a full scale crash test conducted by the Federal Aviation Agency. In 1969 U.S. Secretary of Transportation, John Volpe, recommended to President Richard Nixon that air bags be installed in all automobiles sold in the United States. The proposal has taken far longer to accomplish than was expected, but air bags became available as optional equipment in the 1982 Mercedes, and are now mandated for a phased in introduction by FMVSS 208. Only driver side steering wheel air bags are currently available. An exception is a very limited production sports car, the Porsche 944 Turbo, which offers both passenger and driver air bag system. Passenger side systems are expected to become more widely available in larger cars in the near future.

PROBLEMS WITH SAFETY BELT PERFORMANCE AND USAGE

Serious injury may occur from safety belt usage. Abdominal injury may be caused by impingement of the lap belt on the soft part of the abdomen. Submarining is a phenomenon in which the pelvis sinks into the seat cushion and slips from beneath the lap belt or placement of the belt above the bony pelvis causes impingement of the belt on the soft parts of the abdomen. This impingement may injure the liver, spleen, intestines, bladder, kidney, aorta, inferior vena cava, and/or spine. The first lap belt injury was reported in 1956 by Kowalski and Rost.[16] Smith and Kaufer in 1970 reported distraction injuries of the spine from lap belt usage.[17] Gallop et al. reported that high placement of the belt caused most abdominal injuries (Figures 7 and 8).[18]

The following illustrates a fatal injury caused by lap belt impingement on the abdomen:

A young man was asleep in the front seat of a 1964 Pontiac which collided head-on with a stone wall. His facial lacerations were sutured. He lapsed into irreversable shock because of unrecognized intra-abdominal blood loss, and was discovered to have a torn mesentery. Autopsy photographs revealed a deep abrasion across his abdomen well above the iliac crest and caused by his lap safety belt (Figures 9 and 10).

Submarining or slipping of the bony pelvis from beneath the lap belt appears responsible for some and possibly most lap belt induced abdominal injuries. Seat cushions may be in part responsible for this problem. Seat cushions are typically made of zigzag springs with little resistance to the loading which occurs druing a crash. Typically, the buttocks of a lap belted occupant in a typical production seat may sink nearly to the floor. Race car builders recognized that hard seats with a hop-up to prevent forward excursion of the buttocks or plevis prevented submarining and enhanced lap belt effectiveness.[19] Adomeit experimentally demonstrated the effectiveness of such seat designs.[20] Volkswagen first utilized the design concept in the lower seat cushions of the 1975 Rabbit manufactured in Europe.

The Volkswagen Rabbit seat is a metal pan filled with plastic foam. The forward lip of the seat slopes upward at approximately 45 degrees, effectively preventing downward and forward excursion of a lap belted pelvis in head-on collisions. Similar designs have been incorporated in the rear seats of two European luxury vehicles (Figures 11 and 12).

Proper placement of the lap belt remains essential. The lap belt must be placed on the thighs in front of the bony pelvis. Heavy clothing, obesity, and a slouched posture make proper placement difficult.

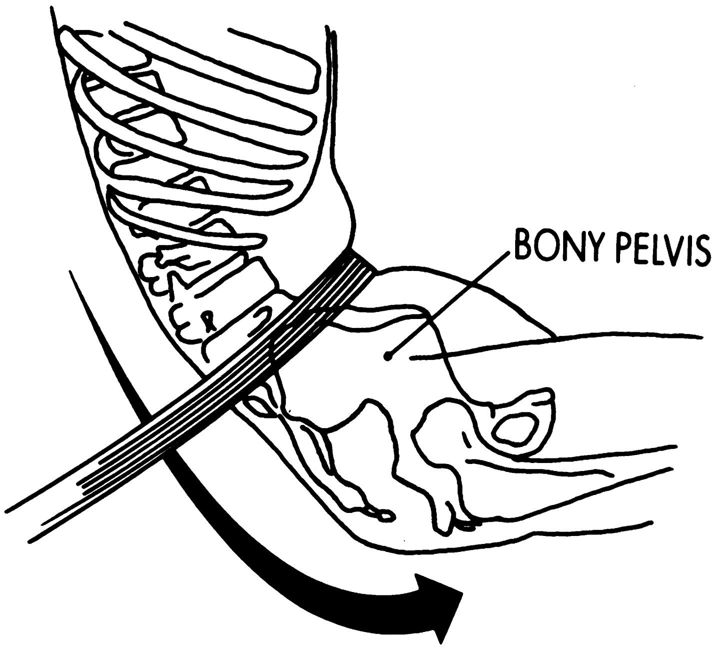


Fig. 7. Submarining is a kinematic phenomena in which the pelvis slips from beneath the lap safety belt causing the belt to impinge on the soft part of the abdomen where serious or fatal injury may occur. Reproduced with permission from *A.A.A.M. Proc. 24*:22.

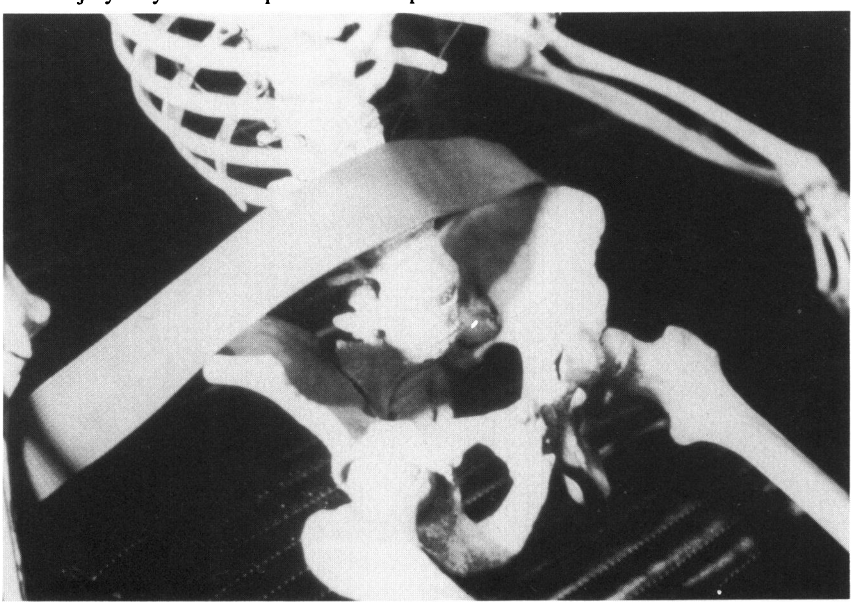


Fig. 8. A lap belt across the abdomen above the bony pelvis will injure the soft tissue structures and organs of the abdomen and may cause distraction (''chance'') fractures of the dorso-lumbar spine.

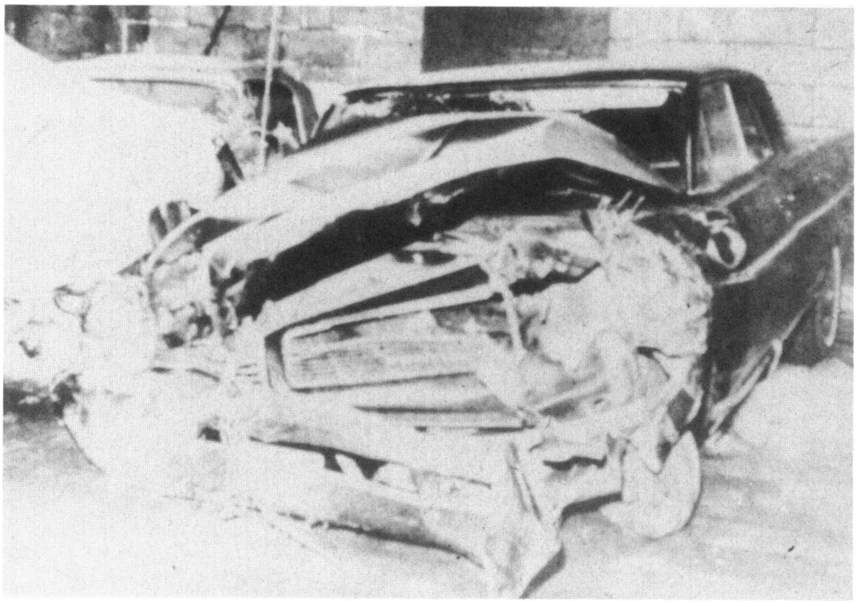


Fig. 9. A 1964 Pontiac impacted a stone wall head on. A young man in the front passenger seat sustained facial lacerations and fatal mesenteric lacerations within his abdomen.

Fig. 10. Autopsy photograph showing a deep abrasion above the iliac crests caused by his lap safety belt.

A second problem is underarm use of the shoulder belt. Six fatalities in addition to two previously reported fatalities were reported in 1987 by States et al. because of underarm use of the shoulder belt.[21] Positioning the shoulder belt under the arm concentrates the load over the mid-abdomen where lacerations of the liver, spleen, intestine, and occasionally the major vessels of the abdomen may occur (Figures 13 and 14).

The following case study illustrates the hazards of underarm shoulder belt use. A 16-year-old girl had turned around after reaching into the rear seat for her purse. The shoulder belt slipped off her shoulder and came to rest under her arm just as the vehicle ran off the roadway into the end of a bridge abutment. She died subsequently because of intra-abdominal hemorrhage from a near transection of her liver (Figures 15 and 16).

A third problem is facial injuries sustained by restrained drivers involved in head-on collisions. In such a collision, the driver's face may impact the steering wheel, rim, or hub causing injuries of the forehead, eyes, facial bones, or jaw (Figures 17 and 18).

The following case illustrates this injury mechanism: An elderly driver collided head-on with the left side of an oncoming vehicle out of control. The accident occurred on a rural state highway with a closing velocity in excess of 70 MPH. She was restrained with a 3-point belt system, but impacted the steering wheel rim with her nose and malar eminences, breaking her nose. The driver of the other vehicle sustained a fatal injury in his cervical spine because of the collision.

Steering wheel air bags are expected to protect drivers against this injury mechanism. Interposition of an air bag between the head and face of a driver and the steering wheel and hub will prevent head contact with the steering wheel.

Last, usage rates of safety belts remains a problem. In New York State safety belt usage rates bottomed out in 1980 and 1981 at about 12%. In part as a result, New York was the first state to enact a safety belt use law in the United States, effective December 1, 1984. Current usage rates are approximately 50%. Education and enforcement appear to be the key to higher usage rates. Our Canadian neighbors advised us of this before our law was enacted.[23] In subsequent studies, Rood et al. in New York State established that a continuous locally sponsored education coupled with education of the police force and increased enforcement can raise usage rates.[24]

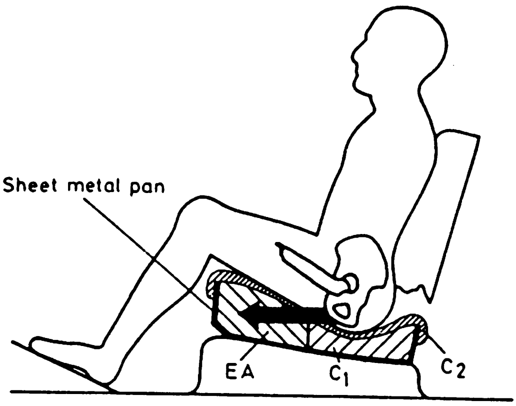


Fig. 11. Adomeit experimentally demonstrated the effectness of upward sloping seat cushion pans for prevention of submarining. Reprinted with permission from *Proceedings of the 19th Stapp Car Crash Conference*. Warrendale, PA, Soc. of Automotive Engineers, 1975.

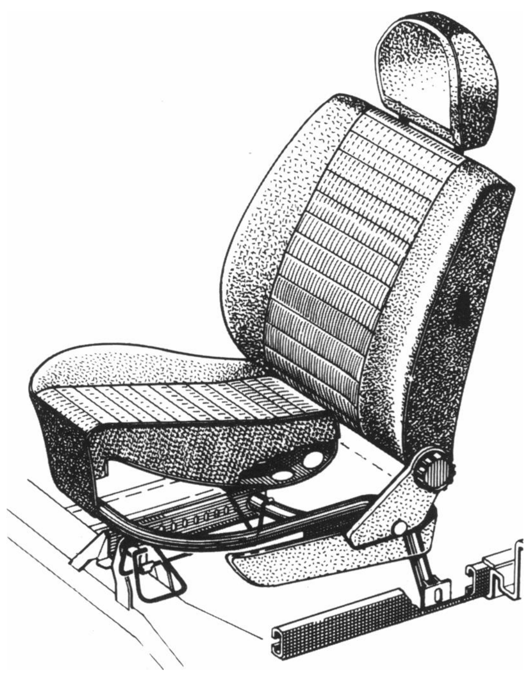


Fig. 12. Diagram of Volkswagen Rabbit seat introduced in 1975 incorporating upward sloping lower seat cushion pan to prevent submarining.

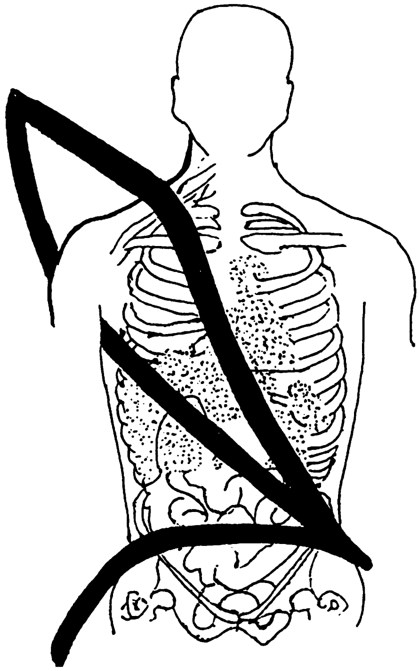
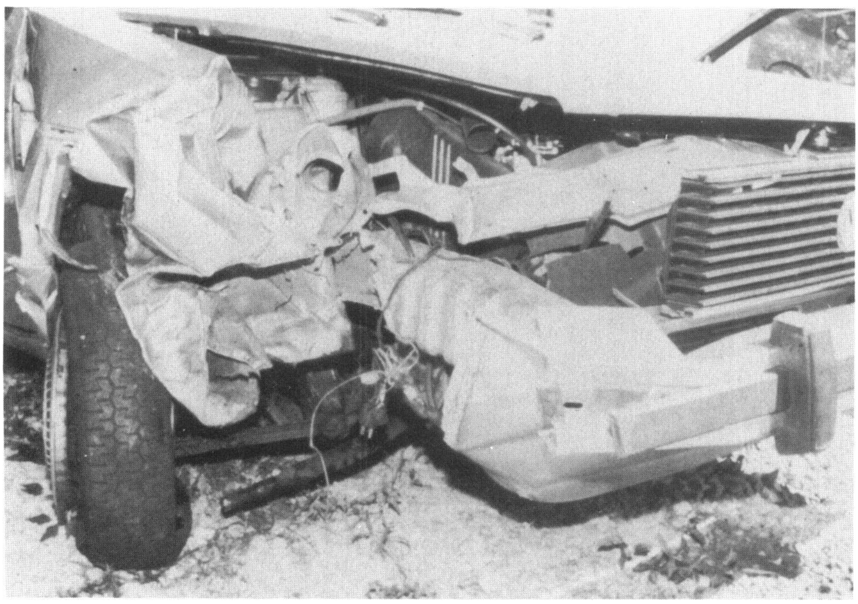


Fig. 13. Under-arm placement of the shoulder belt concentrates loading over the upper abdomen where serious or fatal injury, most commonly to the liver, may occur. Use of the shoulder belt in this position is dangerous and should never be permitted.

Fig. 14. Under-arm placement of the shoulder belt relieves irritation from shoulder belt impingement, but exposes the wearers to serious or fatal abdominal injury.

Figs. 15 and 16. A Volkswagen Rabbit impacted a bridge abuttment with its right front corner. The right front seat passenger sustained a fatal liver laceration from underarm shoulder belt use.



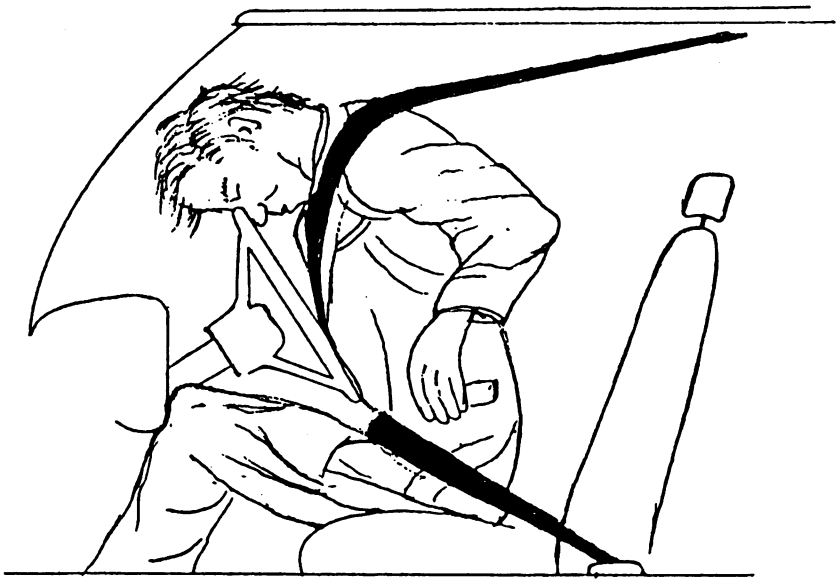


Fig. 17. In severe head-on impacts belted drivers may impact their faces on the steering wheel rim or hub in spite of lap and shoulder belt restraint.

Fig. 18. An elderly woman sustained fractures of her nose and right orbital floor when her Oldsmobile impacted head on a car coming from the opposite direction on a country road.

Summary and Conclusions

Safety belts are highly effective in preventing motorist injuries caused by the second collision, the collision of the occupant with the inside of the vehicle. The use of safety belts was first reported in 1907 and was subsequently developed by Hugh DeHaven, a World War I fighter pilot and engineer, and by John Stapp, a U.S. Army Air Force physician who conducted extensive research in human tolerances and restraint systems. Dr. William Haddon, past administrator of the National Safety Bureau, now the National Highway and Traffic Safety Administration, promulgated safety standards which required the installation of lap and shoulder safety belts in all cars sold in the United States. Safety belts effectively restrain the human body by anchoring the human body with a lap belt at the center of gravity of the human body. The shoulder belt controls the head and upper torso and effectively prevents impact with the forward structures of the vehicle in all but the most severe accidents.

Current problems of safety belts are abdominal injuries resulting from lap belt impingement on the abdomen, underarm use of the shoulder belt resulting in severe upper abdominal injury, facial injuries among belted occupants by impact of the face on the steering wheel and hub, and low safety belt usage rates.

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